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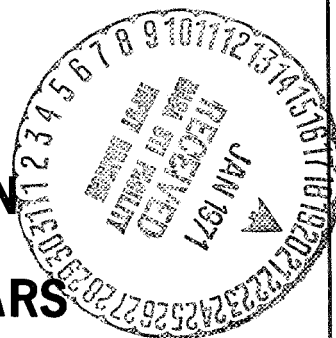
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**NON-THERMAL
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X-STARS AND PULSARS**



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Non-thermal Radiation Emission from X-Stars and Pulsars

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A nonthermal mechanism, for radiation emission from a spinning collapsed star, is based on the effects of the electric field parallel to the co-rotating magnetic field, as allowed by the anomalous resistivity of the surrounding plasma, and of the scattering relative to the field (e. g. , because of plasma collective effects) of the electron energy and momentum. Models for x-ray sources and for pulsar emission are proposed, together with a high-energy particle-acceleration process.

The optical identification of Scorpio X1 with a blue star¹ and the more recent discovery of pulsed x-ray emission from the Crab Nebula pulsar NP0532² have brought to attention the possibility that x-ray sources are stellar objects, probably very condensed stars.^{3,4} We present a plasma emission model that in fact interprets x sources as collapsed stars transforming rotational energy into electromagnetic radiation. A star of this type⁵ results from a rapid process occurring under angular momentum and magnetic flux conservation, and is characterized by high angular velocity ω_0 and magnetic field B . So we assume that a typical x star: (i) is a condensed and rapidly spinning object ($M \cong 0.5 M_\odot$, $R \cong 3 \times 10^{-5} R_\odot$); (ii) has a large co-rotating magnetic field ($B_{\text{surf}} \gtrsim 10^{10}$ G); (iii) is surrounded by a relatively dense

plasma, whose equilibrium transverse to the magnetic field is approximately described by

$$e\mathbf{E}_\perp \left(Z - \frac{n_e}{n_i} \right) + eZ(\mathbf{u}_{i\perp} - \mathbf{u}_{e\perp}) \times \mathbf{B} + m_i(\mathbf{g}_\perp - \mathbf{u}_i \cdot \nabla \mathbf{u}_{i\perp}) = 0. \quad (1)$$

Here we have used standard notation with the subscripts \perp and \parallel indicating components perpendicular and parallel to \mathbf{B} . The relative charge separation between electrons and ions, $e(Z - n_e/n_i)$ is very small and, in virtue of the high values of B , is compensated by a very slow azimuthal drift of the ions relative to the electrons. From this we make the following remarks.

1. Within the "light speed cylinder" ($r < R_c = c/\omega_0$) the electrons are strictly tied to the field lines, and then to the rotation of the star because of its very high conductivity.⁶

2. A large electric field perpendicular to the magnetic field lines arises as a consequence of the star's rotation:

$$\mathbf{E}_\perp \approx -\mathbf{u}_0 \times \mathbf{B}, \quad (2)$$

where $\mathbf{u}_0 = \omega_0 \times \mathbf{r}$ and, in view of the small value of current density transverse to \mathbf{B} as given by Eq. (1), the resistive contribution has been neglected. The parallel electric field $\mathbf{E}_\parallel = -\nabla_\parallel \phi$ is given by

$$\nabla_\parallel^2 \phi = \nabla \cdot (\mathbf{u}_0 \times \mathbf{B}) - 4\pi en_i \left(Z - \frac{n_e}{n_i} \right), \quad (3)$$

where the residual charge separation does not have an important role in the processes that we are considering.

3. A relatively large E_\parallel with acceptable values of the current density $\mathbf{J}_\parallel = -n_e e \mathbf{u}_{e\parallel}$ can be maintained by an anomalous resistivity η_\parallel an larger than the classical one resulting from electron-proton collisions, which is generated by plasma collective effects when E_\parallel or $u_{e\parallel}$ exceed certain critical values,⁸ so that $E_\parallel = \eta_\parallel \text{ an } J_\parallel$. In the vicinity of the star we have approximately

$E_{\perp} \approx 2 \times 10^{10} (\omega B)/(\omega^{\bullet} B_0)$ V/cm, where $\omega^{\bullet} = 10^2$ rad/sec and $B_0 = 10^{10}$ G are typical values. It is then evident that, even if $E_{\parallel} \ll E_{\perp}$, E_{\parallel} is likely to dominate the longitudinal particle motion. Then the electron distribution function, f_e , as is well known from laboratory plasmas subject to strong longitudinal electric fields,⁹ will have a Maxwellian body with a tail extended toward high energies (see Fig. 1), depending on the ratio $E_{\parallel}/E_{\text{run}}$. Here

$$E_{\text{run}} \approx \eta_{\text{cl}} n_e v_{\text{the}}, \quad (4)$$

with η_{cl} the classical resistivity resulting from electron-proton collisions,⁸ and v_{the} the electron thermal velocity. We consider $E_{\parallel}/E_{\text{run}} \gtrsim 1$ so that a relatively large tail of superthermal electron can exist. Notice that in laboratory experiments¹⁰ densities n_s of these fast electrons as large as $10^{-2} n_e$ have been observed.

Mildly relativistic electrons (with $\gamma = \epsilon/mc^2 \sim 1$) in the presence of strong magnetic fields lose their perpendicular energy, emitting cyclotron radiation at frequencies $\omega \approx \Omega_e = 1.76 \times 10^{17} (B/B_0)$ rad/sec, where Ω_e is the electron gyro frequency. Therefore for $B \sim 1 \div 100 \times B_0$ we have emission of x rays. The time scale of electron energy loss is

$$\tau \approx 2.58 \times 10^{-12} (B_0/B)^2 \text{ sec.} \quad (5)$$

If the x star emits from a shell of thickness δ quite close to its surface, as the sharpness of the pulses and the dispersion at radio frequencies for the Crab Nebula pulsar imply, then the total power emitted is roughly $w = 1.5 \times 10^{19} (B/B_0)^2 n_E \delta \text{ erg sec}^{-1}$, where n_E is the number density of emitting electrons. On the other hand, the mean value of the observed power of x-ray sources is $W \sim 10^{36} \text{ erg/sec}$,¹¹ so that $n_E \sim 10^{17} \delta^{-1} \text{ cm}^{-3}$.

The cyclotron emission process can be maintained by transfer of perpendicular energy and momentum to the electrons, for instance, via plasma

collective effects. This mechanism has been well investigated.⁷ In the presence of a plasma wave with frequency ω , particle-wave resonances occur,¹² leading to energy and momentum exchange: $\hbar\omega + \Delta\epsilon_p = 0$, $\hbar\mathbf{k} + \Delta\mathbf{p} = 0$, where $\hbar\omega$ and $\hbar\mathbf{k}$ refer to the excited mode, and $\Delta\epsilon_p$ and $\Delta\mathbf{p}$ to the particle. Now $\Delta\epsilon_{||} = m_e \mathbf{v}_{||} \cdot \Delta\mathbf{v}_{||}$, $\Delta\epsilon_{\perp} = n^0 \hbar\Omega_e$ (n^0 is an integer) and $\Delta\mathbf{p}_{||} = m_e \Delta\mathbf{v}_{||}$, while $\Delta\mathbf{p}_{\perp}$ is taken up by the magnetic field. The resonance condition is then

$$\omega + n^0 \Omega_e - k_{||} v_{||} = 0. \quad (6)$$

Since $\omega_{pe} < \Omega_e$, because of the strong magnetic field, for electron plasma waves with $\omega \sim \omega_{pe}$ Eq. (6) shows that the energy exchanged with the wave is negligible. The main effect is a transfer of longitudinal energy of the electrons into transverse energy. A plasma wave with $\omega \sim \omega_{pe}$ can exist (without being strongly damped) only if $\omega \gg k_{||} v_{the}$, so the electrons participating in the resonance (6) have to be superthermal and belong to the distribution tail that is obtained for $E_{||}/E_{run} \gtrsim 1$. In particular, the relevant theory requires that $(\partial f_e / \partial v_{||})_{v_{||} = \Omega_e / k_{||}}$ be sufficiently large that the process represented by Eq. (6) will not be overcome by the ordinary Landau damping involving particles with $v_{||} = \omega/k_{||} \ll \Omega_e/k_{||}$ (Fig. 1). Thus all of these conditions are likely to be satisfied on a well-localized region of space.

If we assume, according to neutron star models, that the temperature corresponding to the Maxwellian part of the electron distribution is $T_e \sim T_{surf} \approx 10^6 \text{ K}$ ($\sim 100 \text{ eV}$), then $v_{the} \approx 5.93 \times 10^9 \text{ cm/sec}$ and $\eta_{cl} \approx 1.65 \times 10^{-7} [T_e (\text{keV})]^{-3/2} \ln \Lambda = 5.2 \times 10^{-6} \ln \Lambda \text{ Ohm-cm}$, where $\ln \Lambda$ is a well-known and tabulated function of n_e and T_e . Similarly, from Eq. (4) $E_{run} \approx 3.1 \times 10^6 \alpha n/n_0 \text{ V/cm}$, where $n_0 = 10^{20} \text{ cm}^{-3}$ is a typical assumed density (for which $\ln \Lambda = 6.3$), and α is a numerical factor given by $\alpha = 1 - 0.18 \log_{10} (n/n_0)$. Then the condition $E_{||} \gtrsim E_{run}$ can be easily satisfied. Notice that for $n = n_0$ and $E_{||} \ll E_{\perp}$ the charge separation appearing in Eqs. (1) and

(2) is $\sim 10^{-9}$. In particular, the average collision frequency is large, so that the scattering process from parallel to perpendicular velocity of the "tail" electrons can be due to a classical collisional process instead of the one corresponding to Eq. (6).

Recall now that in laboratory plasma experiments⁹ with $\omega_{pe} < \Omega_e$ the observed resistivity is orders of magnitude higher than the classical resistivity over a wide range of E_{\parallel}/E_{run} . This can be attributed to wave-particle interactions of the type discussed above or of other types associated, for instance, with ion-sound or two-stream instabilities. If we take into account only the first type, it can be argued that⁷ $\eta_{an} \approx \eta_{cl} f(\Omega_e/\omega_{pe})$, where f is an increasing function of the argument $\Omega_e/\omega_{pe} = 3.1 \times 10^2 (B/B_0)(n_0/n)^{1/2}$. Therefore a large E_{\parallel} can be compatible with nonprohibitive values of J_{\parallel} . We expect, nevertheless, that a very small fraction of electrons will escape all collisional and collective interactions and attain high energies along the magnetic field.

The current J_{\parallel} will also excite low-frequency modes in the plasma within the "light speed cylinder," with ω less than ω_{pe} and the ion gyro frequency. We may consider, among others,¹³ modes of ion-sound wave type, which depend on $T_e \neq 0$, are longitudinal, propagate along \underline{B} , and are associated with finite electron thermal conductivity or with electron Landau damping along the same direction. These modes can couple with transverse waves that are expected to be strongly polarized. The corresponding radiation should be characterized by frequencies in the radio range with propagation direction closely related to that of the magnetic field. We then expect that x stars should also be radio sources, their spectrum at low frequency depending on the plasma density inside $R_c = c/\omega_0$.

We recall that in our model the direct x-ray emission and the generation of high-energy particles are associated with the electric field E_{\parallel} applied on the dense plasma surrounding a collapsed star. The resulting electron

distribution function, thanks to the presence of plasma collective effects, is compatible with reasonable values of the average electron flow velocity $u_{e\parallel}$, and exhibits a sizeable tail of fast superthermal electrons when $E_{\parallel} \gtrsim (E_{\text{run}})_{\text{eff.}}$, the effective runaway field including also the effects of plasma turbulence.

Then we make the following points.

1. Scorpio X1 is a typical point source that is also observed as a radio and optical source^{1, 15} and its optical emission seems to be correlated with the x-ray counterpart, as shown by the respective fluctuations on the time scale of hours.¹⁶ This correlation can be explained in our model by the fact that high-frequency modes ($\omega \sim \Omega_e$) are most likely to undergo a nonlinear mode-mode coupling¹² (frequency decay) within the plasma accounting for a large part of the optical emission. This process is consistent with the observation that the optical flux is much smaller than the x-ray flux and the optical spectrum is flat.

The fact that we receive continuous radiation from Sco X1 on a large band (from radio to x rays) and that the source is so pointlike, suggests that the plasma density cannot be too large in the regions where the emission in the lower bands occurs. Therefore, with no nebula surrounding a pointlike x star, most of the high-energy particles produced by E_{\parallel} , which escape the effects of collisions and plasma collective effects, will contribute to the high-energy component of cosmic rays.

2. The Crab Nebula x-ray emission is further characterized by the pulsed radiation from NP0532 ($\sim 5 \div 10\%$ of the total), and the steady extended source. So we assume, for instance, that the co-rotating magnetic configuration of this x star does not have its poles aligned with the rotation axis. On the other hand, the emission process is more efficient at the magnetic poles, where the flux lines converge. Thus it is reasonable to expect the x-ray emission to be characterized by a steady background with periodical spikes

superimposed to it when these polar regions point toward the Earth. A similar effect ^{may be} ~~not~~ observed in the case of Sco X1 either because of the absence of well-defined polar regions or because of a geometrical situation that never allows those regions to point to the Earth. The radiation pulses from NP0532 at lower frequencies, notably in the visible range, are characterized by the lack of a steady component. This means that a strong absorption effect is involved. So, with an electron density $n_e \sim n_o = 10^{20} \text{ cm}^{-3}$, $\omega_{pe} > \omega$ for optical and radio frequencies, and only propagation along the magnetic lines can survive. Therefore we expect to receive signals at radio and optical frequencies only when the polar regions come into view. Again we consider the optical emission to have a strong correlation with the x emission, resulting for instance, from a nonlinear process of frequency decay which again is consistent with the smaller energy output in the visible than in the x-ray band.

The extended x-ray source is likely to be due to synchrotron emission by highly relativistic electrons in the nebula magnetic field.¹⁷ The continuous injection of high-energy electrons can be associated with the relatively small electron population that under the influence of $E_{||}$ escapes the effects of inter-particle collisions and collective phenomena and attains very high values of γ . Also, other processes of particle acceleration connected with the co-rotation of the magnetic field are likely to take place around and outside R_c . In this case both mildly and highly relativistic electrons are supplied. So the total effect of these two mechanisms would be a synchrotron emission from the Nebula over a very large spectrum.

3. The slowing down of the star (which is observed in NP0532) determines a decrease of $E_{||}$, while $E_{run} \propto T_e^{-1}$ may increase because of the star's aging. Therefore at a certain stage the ratio $E_{||}/(E_{run})_{eff.}$ may no longer be sufficient to maintain the required tail of fast electrons. In fact, we recall that the appearance of "runaway" electrons is a sharp function of $E_{||}/E_{run}$,

typically of the form¹⁴

$$n_s \propto n_e e^{-E_{\text{run}}/E_{\parallel}}. \quad (7)$$

So an x star should undergo a relatively sudden process of aging after which, since only low-frequency modes would survive as a source of emission, it could still be observable as a radio source. On the other hand, the life-time of an x star may not be determined by this type of emission process, since its associated energy output, typically of order 10^{36} ergs/sec, is well below that required for explaining the slowing down of NP0532. Rather, the very low-frequency radiation from a rotating (magnetic or gravitational) multipole¹⁸ appears to be adequate to explain the gross energy output consistent with the known slowing down.

The aging of a pulsating x star like NP0532 leads naturally to a radio pulsar, according to the argument indicated above, so that only the low-frequency (radio) modes, which are beamed around the magnetic axis remain. In particular, one can expect the sudden transition to a pure radio pulsar to occur relatively early in the star's life, as suggested by the observation of the Vela radio pulsar (PSR0833) whose period is only about three times that of NP0532.

The prediction of pulsed x-ray observation from NP0532, on the basis of the typical frequency Ω_e , was made in the author's paper at the Meeting on the Physical Aspect of Pulsars (Pisa, Scuola Normale Superiore, April 1969).

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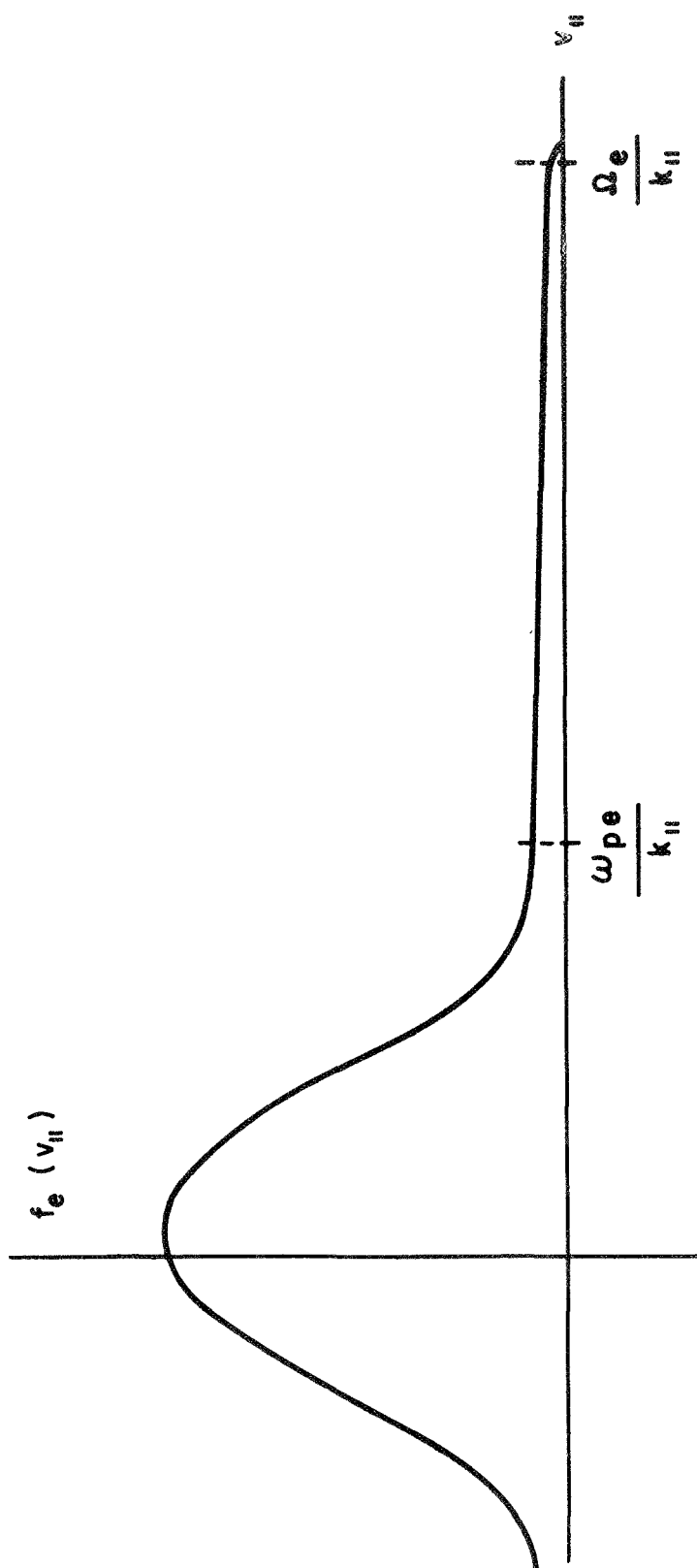


Figure 1 Example of a typical "runaway" distribution, with regions of particle-wave resonance indicated.